NATIONAL RADIO ASTRONOMY OBSERVATORY

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Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)
Establishment of an Interference Temperature	)
Metric to Quantify and Manage Interference and	) ET Docket No. 03-237
to Expand Available Unlicensed Operation in	)
Certain Fixed, Mobile and Satellite Frequency	)
Bands	)

Comments of the
National Radio Astronomy Observatory
Charlottesville, VA 22903

I. Introduction, Background, and Description of this Document

1. National Radio Astronomy Observatory (NRAO) is pleased to provide comments in response to the Commission's Notice of Inquiry and Notice of Proposed Rulemaking (FCC 03-289) regarding Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands (ET Docket No. 03-237).

2. NRAO (http://www.nrao.edu), operated by Associated Universities, Inc., (http://www.aui.edu) under a cooperative agreement with the National Science Foundation, is the largest radio astronomy observatory and one of the largest astronomical observatories of any kind in the world. As such, it is responsible for much of the basic research conducted by the Radio Astronomy Service nationally and internationally. NRAO currently operates the Very Large Array (VLA) in Socorro, New Mexico, the Robert C. Byrd Green Bank Telescope in Green Bank, West Virginia, and the Very Long Baseline Array (VLBA), an array of ten antennas spread across the United States from Hawaii to St. Croix. NRAO is the North American partner for construction of ALMA (Atacama Large Millimeter Array; http://www.alma.nrao.edu) an international facility sited in northern Chile comprising 64+ millimeter/submillimeter wave antennas designed to observe up to 1 THz. NRAO provides engineering assistance throughout the basic research community, for instance by fabricating the low-noise amplifiers currently exploring the cosmic microwave background (see para. A5 below) on board the incomparable Wilkinson MAP satellite (http://map.gsfc.nasa.gov/).

3. As a public institution, and in its contribution to the stewardship of radio astronomy on behalf of the American people, the NRAO is obligated to express its concern for the continued success of its operations. As a passive service, radio astronomy depends heavily upon the

regulatory process. In turn, evidence of radio astronomy's long involvement with the processes of spectrum management is manifested in the many statutory protections which have been afforded to the Radio Astronomy Service in the form of protected bands, shared allocations, regulatory footnotes, etc.

4. The NOI/NPRM FCC 03-289 is a complex document and NRAO's comments do not respond to more than a small part of it. The present document is divided into a main body (Sections II-VII) wherein NRAO comments on a few important points, followed by an Appendix. The Appendix discusses the relationship between temperature and the electromagnetic spectrum in terms relevant to the Radio Astronomy Service and its continued operation within the regulatory regime, present and projected, while providing support and background for the remarks made in the main text.

II. Opportunities for new spectrum access under an interference temperature cap are not properly represented in Figure 1 of the NOI.

5. Figure 1 of the NOI, discussed at para. 15 there, is intended to convey the opportunities which exist for new spectrum access in a schematized spectral landscape under an interference temperature cap. NRAO believes that this figure, no matter how schematic in nature, nonetheless fails to convey an accurate impression of the opportunities which truly exist in the diagramed environment. In essence, there are fewer opportunities for new access without violating the cap and diminishing the service range of the radio station. The suggested point of new access does not exist, although the deleterious effect on the landscape of an additional emitter there might be ameliorated by unspecified protective measures carrying a cost not foreseen by the diagram.

6. The landscape in Figure 1 of the NOI must, of course, be considered as applying to a narrow slice of the frequency spectrum in a particular direction. However, to the extent that the diagram is supposed to be general, considerations of the use of other frequencies or directions should not be employed to alleviate difficulties encountered in this slice. Using other frequencies to provide an access point for underlay technology is mentioned in the NOI at para. 16 and footnote 17.

7. Note that, in Figure 1 of the NOI, the radio station signal has broad skirts on the intensity falloff of its signal, characteristic of the $1/distance^2$ spatial spreading of its isotropically-radiated signal. Furthermore, this is the only propagation effect which is considered in the diagram, so the spatial scale of the schematic is compact in some sense. All signal transmission is line-of-sight.

8. However, none of the localized sources which exist under the level of the interference cap in Figure 1 of the NOI have these skirts; many are spindle-shaped and some are manifestly unphysically recurved back upon themselves. They do not represent real radiators, which, unless completely confined (and therefore of dubious utility) or otherwise directed (in which case they hardly belong in the diagram) will have the same $1/distance^2$ profile as the radio station itself.

9. Consider now the introduction, directly under the downward arrow labeled "New Opportunities For Spectrum Access," in Figure 1 of the NOI, of a new source of radiation which propagates over the landscape. Including the $1/distance^2$ skirts on any such signal will produce some additional radiated power even at the peak immediately to the right of the arrow, where the

interference temperature cap appears to be met. Thus the interference temperature cap will be exceeded where previously it was met and, quite generally, further opportunities for further access are limited across the entire landscape as soon as the interference temperature cap is met anywhere within it.

10. Other, protective measures might keep the interference temperature cap from being violated meaningfully, despite the literal violation. But these will incur costs which are not foreseen by the diagram.

11. This discussion highlights the necessity of conveying information regarding the state of the distant electromagnetic environment across the schematic landscape. However, because it is limited to one spatial slice, it fails to convey the importance of and additional complexity introduced by the anisotropies (directional aspects) of the real landscape. Some of these are briefly mentioned below at A6, A7, A12, and A15.

III. Use of rural areas currently enjoying low spectrum occupation.

12. The need to restrain the possible behavior of unlicensed and other opportunistic devices (NOI at paras 7, 11, 12, 14 and throughout) becomes especially acute in regions, like the National Radio Quiet Zone (http://www.gb.nrao.edu/nrqz/nrqz.html), where the electromagnetic environment may appear to an uninformed cognitive device to be especially underutilized. Even well behaved devices which are designed to operate opportunistically in their access to unoccupied spectrum may, however inadvertently, become unwelcome intruders or even predators in remote areas (a specific example, based on the NPRM's inquiry into unlicensed operation at 6650 MHz is discussed here at 16-20).

13. In light of this, the NRAO wishes to raise two concerns:

• Some of the means discussed in the NOI to disseminate information on the state of the electromagnetic environment to unlicensed devices needing such information are impracticable in truly rural areas (like using the SCA channel of FM broadcasts, NOI at 14).

• The use of transmitters to inform devices that the environment is particularly quiet, and should be kept so, seems contradictory. Any means of such control should avoid placing additional burdens on the spectrum.

IV. All interference beyond the tolerance threshold is harmful interference to radio astronomy.

14. The NOI (para. 28, 1st bulleted point) inquires, for a given service operating in a particular frequency band, how much interference can be tolerated before it is considered harmful. As discussed below at para. A15, the Radio Astronomy Service operates in the presence of, and with tolerance for, interference, but all interference beyond the tolerance threshold is harmful.

V. Passive uses of the spectrum are the most sensitive to interference.

15. At para. 21, seventh bulleted point, the NOI requests comment on how to set interference temperature limits in cases of shared allocations, and how to determine which service is most susceptible to interference. In general, the tolerance thresholds presently accorded to radio astronomy translate directly into the proposed interference metric, as discussed at para. 21 here (first bulleted point). The NOI does not use the terms "active" or "passive" although it is clearly addressed to active uses of the spectrum.   NRAO believes that the services most susceptible to interference are often the passive users, including the Radio Astronomy Service.

VI. Retention of current limits on unlicensed operations in the band 6650-6675.2 MHz is needed to protect operations of the Radio Astronomy Service.

16. The NPRM seeks comment on whether it might be necessary to preclude unlicensed operation in the 6650-6675.2 MHz band to protect radio astronomy operations (para. 48).

17. Footnote ITU-R 5.458 A states "In making assignments in the band 6700-7075 MHz to space stations of the Fixed-Satellite Service, administrations are urged to take all practicable steps to protect spectral line observations of the Radio Astronomy Service in the band 6650-6675.2 MHz from harmful interference from unwanted emissions."

18. For spectral line observations at this frequency, the nominal suggested interference threshold power flux density limit given in Table 2 of ITU-R RA.769 (05-03), for operations of a single radio dish like the Robert C. Byrd Green Bank Telescope (GBT: http://www.gb.nrao.edu), is -178.9 dBW/m^2. Current permissible levels for unlicensed operation at 6650 MHz cited in the NPRM at para. 37 are -41.25 dBm. This corresponds to a minimum line of sight separation distance of 68 km, comparable to the extent of the entire national radio quiet zone about the GBT, if the threshold limits are to be observed. This is consistent with the absence of coordination requirements on unlicensed and mobile devices within the quiet zone.

19. Higher-power unlicensed operations such as are discussed in the NPRM (para. 43) would result in nominal separation distances so great that the Radio Astronomy Service could be adversely affected by even every distant devices, should they happen to be located within line of sight of a radio astronomy station.

20. For this reason, and unless and until a mechanism is put in place to prevent operation of unlicensed devices at higher power levels within expanded exclusion zones around the stations of the Radio Astronomy Service, NRAO favors retaining the current limits on power levels associated with unlicensed operation in the 6650-6675.2 MHz band.

VII. Maintenance of the current practices to protect the Radio Astronomy Service from unlicensed operations.

21. The NOI inquires (para. 21, last bulleted point) whether to continue to use the same protective procedures for some services. Such a need is demonstrated in one particular case at para. 16-20 here. NRAO strongly endorses the concept that current levels of protection afforded to the Radio Astronomy Service should not be weakened under a new regulatory regime, no

matter the metric upon which it is based. In this regard, NRAO wishes to make several further points with reference to issues raised in the NOI/NPRM.

- The protections currently afforded to the Radio Astronomy Service are typically expressed as maximum permitted levels, measured *in situ* at the radio astronomy station. These may be readily expressed as temperatures, as envisioned in the NOI or given the considerations of the Appendix (e.g., A3 and A8). Thus the protections afforded to the Radio Astronomy Service may in general be easily transferred back and forth to the metric of temperature: current and future practice may (depending on the outcome of the rulemaking process) largely coincide even if they are described differently. NRAO refrains, however, from suggesting that the NOI constitutes a description of the electromagnetic environment generally as a series of radio quiet zones.

- The temperatures which result from converting the present permitted power limits at radio astronomy stations to the new metric will not in general be in more convenient or intuitive units than under the current metrics. The conversion from power spectral density, etc. to temperature will generally result in temperatures which require scientific notation for their expression (see para. A9 here).

- Creating a new regulatory regime predicated on controlling the conditions experienced locally, as envisioned by the NOI, is not necessarily the same as adopting a temperature metric. For instance, the current protections afforded to radio astronomy, although they attempt to control the noise levels at the stations of the Radio Astronomy Service, do not employ a temperature metric. The same regulatory regime could be created using the present metrics of power spectral density, flux, etc.

Appendix A

A1. The discussion which follows is intended to provide some background on the use of temperature to describe the electromagnetic spectrum, within the context of the operation of one passive service, radio astronomy. References to the discussion in the Appendix are made in the main body of this comment, as noted above. The standard general reference to the basics of radio astronomy is the textbook "Radio Astronomy" by John D. Kraus. A more advanced treatment is contained in the treatise "Interferometry and Synthesis in Radio Astronomy" by A. Richard Thompson et al.

AI. The relationship between temperature and electromagnetic spectrum.

A2. The relationship between the temperature of a body, understood as a measure of the quantity of heat in the body, and the spectrum of electromagnetic radiation emitted by the body, was established by Planck at the end of the 19th century. This is the famous Planck law of radiation from a black-body, the black-body being a theoretically perfect emitter and absorber which real objects approximate to varying degrees.

A3. Another important connection between the temperature and the electromagnetic spectrum was noted by Nyquist (1927), namely that the power spectral density (watt-sec/Hz) in a resistor at temperature T is just kT, k being Boltzmann's constant 1.38×10^{-23} Watt-sec/Kelvin. Resistors being associated with loss, it happens that true signal loss in a medium at temperature T (as opposed to the signal diminution which occurs during line of sight propagation from normal spatial spreading) is replaced by thermal noise at temperature T. For instance if a fraction f of an incoming celestial signal is absorbed by the atmosphere, that fraction is simultaneously replaced by a quantity of noise at the temperature of the atmosphere. If the incoming signal is characterized by a small temperature, even a very small atmospheric loss may completely obscure the incoming radiation. In the extreme, when the atmosphere is opaque, it also becomes a good radiator at its characteristic temperature and the sky brightens to (roughly) room temperature, absorbing all incoming radiation.

A4. The completing link in this chain connecting temperature to electromagnetic radiation was provided by Dicke (1946) who showed that an electrical antenna, immersed in a cavity (electrically sealed box) whose walls are held at temperature T, will, in a sense, be electrically heated to that temperature. The signal received by the antenna in the cavity is equivalent to terminating the antenna across a resistor at temperature T: the power spectral density received by the antenna is kT. This is the origin of the antenna temperature concept referenced in the NOI at footnote 14. An antenna actually senses the temperature via its receipt of electromagnetic radiation in this ideal case; where it is immersed in and perfectly coupled to an ideal environment which radiates at temperature T according to the Planck law. The discussion here slights some quantum effects and ignores the noise associated with the detection of individual photons, both of which become important at higher frequencies.

A5. In 1965, it was discovered that the entire universe is glowing as a result of radiation left over from the primordial event which gave birth to the Universe. That is, after accounting for all other sources of radiation, Penzias and Wilson discovered that, as Dicke had imagined, their communications antenna was behaving as if it was immersed in a cavity at a temperature of about 3 Kelvins. A more precise modern value is 2.73K, and the cavity in this case is the

Universe. Subsequent study of this so-called cosmic microwave background radiation by the Radio astronomy service has provided the most detailed information on the basic structure of space-time and the early history of the Universe (http://map.gsfc.nasa.gov/).

AII. Coupling, anisotropy, wind-chill, and the interference temperature.

A6. The preceding paragraphs A1-A5 describe situations in which emitted radiation is related to a temperature; such are called thermal emitters. They also describe some situations where a thermal temperature is directly related to the electrical temperature of an antenna: the electrical temperature of an antenna reflects the physical temperature of the emitter perfectly when the antenna is perfectly coupled to the radiation from a perfect radiator. In cases where the coupling is less than perfect, the antenna temperature will deviate from the temperature of the emitter. It is this situation—where conscious attempts have been made to isolate an antenna from its environment—which permits operation of many radio services with a noise floor well below the thermal noise floor provided by the natural environment.

A7. In human terms, the fact that different environmental conditions may prevail at the same temperature has resulted in construction of "wind-chill factors" which attempt to describe the coupling between the human body and its environment. Windy conditions feel colder because the capacity of the environment to remove heat is greater for greater air flow. One turns away from the wind under such situations, if this is practicable. The point is that the environment is frequently anisotropic—different-seeming in different directions. Direction and degree of coupling to the environment together determine what temperature is sensed, no matter what the temperature is.

AIII. Formal equivalence between energy (Watt-sec), power spectral density (Watt/Hz) and temperature.

A8. The formal dimensional equivalence between an amount of energy E (Watt-sec), power spectral density PSD (Watt/Hz) and the expression kT means that any energy E or power spectral density PSD may be expressed formally as an equivalent temperature, by the simple expedient of taking the quotient E/k or PSD/k. This is true even if the source of the radiation is not thermal, or when coupling is poor and the equivalent temperature does not directly represent the temperature of the radiating body. The question before the FCC and the public is whether this expedient adds value to spectrum use and the regulatory environment.

AIV. Distinctions between the use of temperature and other metrics.

A9. To understand the subtle distinctions among flux, power spectral density, antenna and physical temperature, consider the weakest signals detected by the radio astronomy service. By observing for 300 hours over a bandwidth of order 30 MHz, the Very Large Array of the National Radio Astronomy Observatory (http://www.vla.nrao.edu) can map the heavens to a noise level (rms error in sky brightness) $3 \times 10^{-32} W/m^2/Hz$ or -355 dBW/Hz received by an isotropic antenna at a wavelength of 3.7cm. The weakest believable detected signals in the presence of this noise have power density levels -350 dBW/Hz, corresponding to antenna temperatures of 2.4×10^{-14} Kelvins, as observed by an isotropic antenna (0 dBi). Similarly, small equivalent temperatures occur when protection levels afforded to radio astronomy are converted to temperature according to the considerations of A8 (as noted above at para. 21).

A10. Of course such signals are weak because they travel vast distances to reach us (the means by which one may detect such weak signals while immersed in an environment at 300 K is considered below at paragraphs A13 and beyond). The emitters themselves are distant, very powerful examples of objects like quasars which can been seen over the length and breadth of the Universe. When examined in detail, quasars are found to be emitting with characteristic temperatures up to 10^{12} K. That is, a Planck black-body of the same apparent size as the emitter in a quasar would need to have this temperature to reproduce even the very modest amount of energy received by a radio telescope.

A11. In fact, the hottest bodies which persist in nature are the massive gas clouds found in clusters of galaxies; these are heated to true temperatures of as much as 10^9 K, which is hotter than in the interiors of many stars (the cluster gas is too tenuous to have nuclear reactions but emits copious X-rays). The temperature of 10^{12} K inferred for the radiation mechanism of quasars is not directly related to the heat or temperature of the quasar. Instead, electrons accelerated to nearly the speed of light spiral in intense magnetic fields, driven by the presence of supermassive black holes.

AV. Costs associated with directionality and resolution of anisotropy.

A12. The previous example may seem overly abstruse. However, there is a direct terrestrial analog; imagine focusing a high gain antenna on the transmitter of a distant, weak radio station. If the gain is high enough, the antenna temperature will be found to be just as physically unreasonable as in the astronomy case: the source of the emission is not thermal (related to its heat) and the antenna measurement will reflect this. Key is to resolve the transmitting signal in angle, at least partially. Yet, spatial resolution, usually associated also with gain, is expensive in terms of the required physical structure. For instance, a device operating at the frequency of a GSM phone in the US (1900 MHz) would need to be perhaps one foot across just to tell front from back. This of course has implications for unlicensed devices if they are to sense their environment.

AVI. Detecting weak signals in a comparatively high temperature environment.

A13. Consider also the fact that the environment at room temperature is at a temperature of, roughly, 300 K. The spectrum of electromagnetic radiation emitted by the ground, atmosphere, trees, *etc.* is characterized by this entirely non-negligible temperature. Yet, it is manifestly not the case that the ambient noise floor is characterized by a temperature of 300 K for radio astronomy. For instance, at 1400 MHz, a radio telescope like the Robert C. Byrd Green Bank Telescope (http://www.gb.nrao.edu) is characterized by a total noise of 15 K, only 1-2 K of which is due to pickup of radiation from the ground. The atmosphere, through which the telescope must observe, is transparent to incoming signals, and (see para. A3 above) so does not provide any substantial noise contribution.

A14. Thus, even though it is immersed in a high temperature environment, a device may use non-uniformities and anisotropies to find clear paths to higher sensitivity. However, the cost can be high; for radio astronomy, the use of large, high gain antennas typically costing tens of millions of dollars sighted in very remote areas.

AVII. Slimness of margin for harmful interference.

A15. At para. A9 it was pointed out that the radio astronomy service reliably detects the presence of celestial sources of very low antenna temperature. Understanding how this is done provides insight into the working of this passive service. One important element is to isolate the telescope from its environment; another is to use the most sensitive electronics, *etc.* to achieve the lowest possible noise floor. Once this is done, the 30 MHz bandwidth (para. A9) of observation, integrated (summed over) for 300 hours (300 x 3600 sec $\sim 10^6$ sec) in two polarizations, uses a channel whose capacity would otherwise have been 30 MHz x 2×10^6 sec $\sim 10^{14}$ bits to identify a weak source at, say, the 100:1 confidence level.

A16. The efficiency of the radio astronomy use might appear very low. However, the signal detected represents genuinely new empirical information about the Universe.

A17. The sensitivity of radio astronomy operations depends critically upon the random nature of thermal noise and the presence of stationary (stable) conditions during observing. The fact that the sensitivity continues to increase as the period and bandwidth of observation are extended (specifically, the noise level should decrease as the square-root of the product of bandwidth and observing time) is the result of the careful calibration and removal of any systematic effects which change over time or across the band within the observing apparatus. To achieve maximum sensitivity, each instant of observing and each slice of spectrum must be statistically identical to all the others.

A18. Interference from discrete sources (in space, time, or frequency) violates this condition; moments of interference are different. Instances of interference are like needles in the haystack; keenly felt when encountered, but very hard to find. Yet, if not recognized and ameliorated—typically by throwing out time slices of the data -- they may cause artifacts which are hard to recognize as false in the final result.
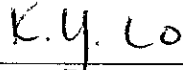
AVIII. Astronomical nomenclature.

A19. The NOI somewhat misuses astronomical nomenclature in footnote17 where it suggests that "Galactic noise is produced by Solar, cosmic and other extraterrestrial phenomena . . ." The word "Galactic" refers more properly to regions of the Milky Way beyond the Solar System while the cosmos is the rest of the Universe beyond the sphere of the Earth. Thus a correct statement would have been "Cosmic noise is produced by Solar, Galactic and other extraterrestrial phenomena . . ."
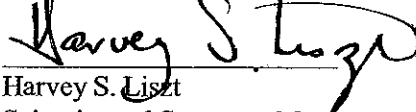
Respectfully submitted,

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